THESES OF THE DOCTORAL DISSERTATION

Modeling and quantitative analysis of collective motion of organisms

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Budapest, Hungary
2010

Background

The living world provides many fascinating examples of collective motion, during which individuals act together with and react to one another, often displaying impressive levels of coordination. The development of technology has made the scientific study of this phenomenon very current in the last one and a half or two decades. The development of computer technology and robotics has opened new opportunities for collective motion in artificial systems. Understanding of organisms' collective motion could help exploit these opportunities. One possible approach is the exploration of models to obtain insight into the laws of such collective phenomena, but furthermore, it is essential that measurements and experimental studies on the subject are taken.

After the earliest computer models that described collective motion the first work with a physics approach was developed in 1995 (Vicsek *et al.*, 1995), and became well known as Vicsek Model (VM) and is generally accepted by the scientific community. The model describes the movement of self-propelled particles (SPPs) in discrete time steps: the particles move with constant speed and determine the average velocity of their neighbors in a fixed radius of their surroundings, using this direction for the next step with some perturbation in a form of additional difference. At low noise the particles move in an ordered manner. By increasing the noise term a disordered-ordered transition takes place in the system, which is a continuous, second-order phase transition according to the first studies.

The VM was carefully examined in many various ways by the scientific community studying collective motion. The statement of the original article on the order of phase transition was disputed by a French research group led by Hugues Chaté (Grégoire and Chaté, 2004). Their findings were inconsistent with the conclusions of the original article. One aim of my thesis was to clarify the causes of the inconsistency.

Further study of the model and the understanding of the apparently contradictory results raised new issues. In the model, the distance travelled by a particle during a time step can be can be smaller (small velocity) or comparable to or even larger (large velocity) than the radius of the interaction. The model shows a new type of behavior in the large velocity regime. The study of the large velocity regime showed that boundary conditions have an important role, as they may cause artificial effects (e.g. symmetry breaking).

Further we proposed and studied an extended variant of the VM, where we analyzed the effect of taking into account the acceleration of neighboring particles as a separate term, independent of the their velocities.

The theme of further scientific publications presented in the thesis is the quantitative observation of animal movements (of individuals and groups). High-precision equipment, the first generation of the state-of-the-art GPS receivers opened the possibility to track the flight path of birds with relatively large mass (peregrine falcon, white stork). I joined this research after the data collection period, and I analyzed and compared the soaring flight strategies of birds and human pilots (paragliders, hang gliders). I investigated how efficiently can this complex task be solved by the soaring masters of the living world.

The second generation of our GPS receivers enabled us to measure the track log of much smaller birds (pigeons) that fly in groups. Earlier similar experiments were only carried out for birds flying in pairs, and the equipment provided the flight data with lower temporal and spatial resolution. We raised the question how the path of the flock is formed by the collective decision-making of the birds. In the literature, essentially two options were considered. In the first approach, one or a small number of strong leaders are able to rule the group's movement, the others follow these leaders. In the other case, each individual contributes equally to the collective decision, and the group's decision is formed by a consensus. My quantitative examinations revealed a third, intermediate possibility.

New scientific results

1. I investigated the SPP Scalar Noise Model (Vicsek *et al.*, 1995) taking into account findings from a subsequent work (Grégoire and Chaté, 2004) disputing the results of the original article.

> a) The findings of the original article were confirmed: the phase transition in the original model is continuous.
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> b) The reasons behind the apparently contradictory results were clarified.
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> c) An extension of the model to large particle velocities uncovered a first-order phase transition. The impact of the periodical boundary condition is very difficult to separate.
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> d) The conclusions of the two-dimensional model were further confirmed by a study of the model extended to three dimensions.

2. A three-dimensional SPP model extended by the addition of an acceleration term was suggested and studied to produce a more realistic model for the collective motion of organisms and possibly nonliving units (robots). Here, the movement of each particle depends on both the velocity and the acceleration of its neighbors. A strategy parameter (s) was defined to express the relative influence of the velocity (s) and acceleration ($1-s$) on the velocity vector of the focal particle.

> a) A novel type of phase transition was identified as a function of the behavioral s strategy parameter.
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> b) I showed that information exchange between particles, a relevant quantity in biology and in system control, is maximal near the critical point of the phase-transition.

3. The soaring flight strategies of birds (white stork, peregrine falcon) and human pilots (paragliders, hang gliders) were analyzed based on high temporal and spatial resolution GPS trajectories.

> a) I found that birds reproduce the MacCready formula – the theoretically optimal rule for maximizing the flight distance during a given time (spent with thermalling and gliding) – for calculating the best gliding angle before an upcoming thermal.
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> b) I showed that top-ranked competitive pilots (knowing the theory and with the aid of their equipment) are able to implement an optimal strategy to the same level as birds.

4. The development of technology opened new ways for studying the collective motion of birds. I analyzed GPS track logs of homing pigeons flying in flocks of up to 10 birds using a variety of correlation functions inspired by approaches common in statistical physics. Leading roles in pairwise interactions were detected on the basis of characteristic delay times between birds' directional choices.

a) I found a well-defined hierarchy among flock members.

b) The average spatial position of a pigeon within the flock strongly correlates with its place in the hierarchy, leaders occupying positions near the front of the flock.

c) Our data suggest that leaders also tend to demonstrate more accurate solo navigation. The leaders are not the fastest birds, thus they are not necessary able to arrive home earlier than the others but it seems that they are able to fly home on a shorter path.

d) In agreement with laboratory studies of hemispheric specialisation found in the literature, laterality effects were found. When birds perceive a particular partner predominantly through the left eye they respond more quickly and/or strongly to its movements.

Publications relevant to the doctoral dissertation

[1] Máté Nagy, István Daruka, Tamás Vicsek:
„New aspects of the continuous phase transition in the scalar noise model (SNM) of collective motion"
Physica A **373**, 445-454 (2007).

[2] Balázs Gönci, Máté Nagy, Tamás Vicsek:
„Phase transition in the scalar noise model of collective motion in three dimensions"
Eur. Phys. J. Special Topics **157**, 53-59 (2008).

[3] Péter Szabó, Máté Nagy, Tamás Vicsek:
„Transitions in a self-propelled-particles model with coupling of accelerations"
Phys. Rev. E **79**, 021908 (2009).

[4] Zsuzsa Ákos, Máté Nagy, Tamás Vicsek:
„Comparing bird and human soaring strategies"
Proc. Natl. Acad. Sci. USA **105**(11), 4139-43 (2008).

[5] Máté Nagy, Zsuzsa Ákos, Dora Biro, Tamás Vicsek:
„Hierarchical group dynamics in pigeon flocks"
Nature **464**, 890-893 (2010).